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Studies of necessary freezing time

G. Lorentzen

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by

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Summary in English

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Foreword.

The Norwegian production of frozen herring is at present approximately 50,000 tonnes annually and increasing. Of this amount a major portion is brine-frozen in half-boxes (50 kg.)

It became evident at an early point in time that brine-freezing increases rancidity during subsequent storage and also causes other disadvantages. The rancidity decreases the value of the herring both as a nutrient and as bait. The tendency has therefore been to turn increasingly to dry freezing of fish, and then primarily to air-blast freezing, also for herring.

A common argument against air-blast freezing has been that it takes longer and requires larger and more expensive installations than brine-freezing. This is true of course. Up to now a satisfactory basis for a reliable calculation of the necessary freezing time has been lacking. Such a basis is necessary in order to determine the correct size for a freezer plant. This study aims to provide the material for such a basis.

Up to now air-blast freezing of herring has been carried out in half-boxes of the same type as those used in brine-freezing (Standard half-box NS 443). It is, however, obvious that rational air freezing based on conventional methods requires a changeover to other, more suitable packaging. The study therefore also includes a special type of cardboard carton designed for that purpose.

The studies were carried out in 1954 - 56 at the

Institute for Refrigeration Technology, at the Technical College of Norway (Norges tekniske høgskole) and were, in part, final papers by candidates Svein Bjørdal, Evert Eriksson and Lars Nerbø. Einar Brendeng, Engineer at the Institute, was responsible for the set-up of the experiments, and some of the measurements and calculations were carried out by scientific assistant H.J. Kopstad. The study was made possible by financial support from Sarpsborg Pap-og Papir-industri A/S. We are also grateful to the firm Arne Bjørseth A/S for their permission to carry out some of the measurements in their freezer plant and for the free delivery of some of the herring used in the experiments.

Purpose, Scope and Execution of the Study.

The purpose of the study was to determine how the most important variables, particularly air temperature and velocity, influence the freezing time of herring in a couple of types of packaging in question. The study also included temperature equalization after the package had been removed from the freezer and placed in the storage area.

The herrings were packed either in standard half-boxes ("freezer boxes") or in special cartons of compressed cardboard. The sizes are shown in Table I. Experiments were carried out on packaginging both with and without lids during freezing. The cartons were also examined to determine how freezing time was influenced by the addition of water and alginate jelly, which occupied the empty spaces between the herring.

TABLE I

Sizes of packaging examined

Type of packaging	Inside measurement.mm Length	Width	Height	Thickness, mm Bottom	Cover	Sides	Content Kg (approx)
Standard half-box	810	480	165	10/13	10/13	13/15	52
Compressed cardboard box	645	405	105	2	2	2 or 2+2	22

For some of the experiments,freezing took place in a special small freezer tunnel as shown in Fig. 1. The entire

tunnel was placed in a freezer with a fairly constant temperature of approximately -30°C. Later, the studies were transferred to the new air-blast freezer of the laboratory (Fig.2), where the operating temperature was by and large -40°C. The air velocity in both cases was adjusted mainly by dampers, and varied between 2 and 12 m/sec. A few experiments were also carried out using "still refrigeration" at approximately -30°C in one of the laboratory freezers.

The air velocity was measured at many points around the product to be frozen, in part, by pitot tubes and, in part, by velocity meters, which had been adjusted. It was unavoidable that the velocity varied somewhat over the cross section, despite attempts to equalize it by placing suitable deflectors in the air current. In the following, when air velocity is discussed, then the mean velocity over the surface of the packaging at 4-5 cm 8.
distance is meant. The tolerance for velocity measurements in experiments no. 1 to 30 is estimated at $\pm$ 15%, for the remainder at $\pm$8%. This inaccuracy plays a secondary role in the relationship to the natural dispersion for other reasons, as freezing time only decreases relatively slowly at increasing air velocity.

The temperature of the air before entering and after exiting the item to be frozen and at a large number of points in the herrings was measured by 0.5 mm copper-constantan thermocouples. The thermocouples were introdudced into the middle of individual herrings along the backbone, in order to avoid any effect from air currents and heat conduction along the

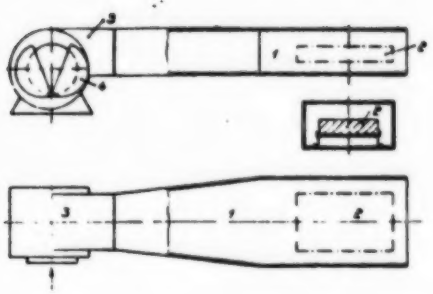

Figure 1. Simple freezer tunnel, placed in freezer at approx. - 30°C. 1: Tunnel. 2: Box or carton with herring. 3: Centrifugal fan. 4: Damper for adjustment of amount of air.

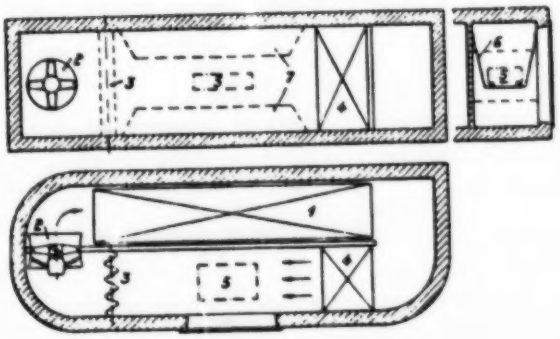

Figure 2. New freezer tunnel in the laboratory. 1: Air cooler. 2: Axial fan. 3: Damper for adjustment of amount of air. 4: "Honey-comb" insert for equalizing air velocity over the cross section. 5: Test box or carton. 6: Hangers. 7: Inserts to achieve greatest possible velocities

thermocouple wire. The measuring points were placed at various depths in the box, distributed in groups transversely through the herring mass. During the first experiments, a light spot galvanometer was used for measuring, with readings at regular intervals. Later, recording electronic potentiometers were used. 9. In both cases the accuracy was better than $\pm$ 1/2 ^{o}C.

In accordance with common procedure the herring was not poured in but placed in the packaging and evened out manually. The boxes were filled to between 49 and 55 kg, the cartons from 22.5 to 26 kg. About 3 kg less herring was in the cartons when alginate jelly was used. Most of experiments were carried out in the fall with whatever type of herring was available at that time. This was mainly fat herring and some small herring. Some measurements were also carried out on large herring and young herring*. The herrings were, by and large, fresh and good, and they were always placed in the freezer immediately after packing to avoid giving them a chance to collapse more than usual. In some cases, the same herrings were frozen several times, for financial reasons. Previously frozen herrings were then mainly packed in packaging with lid, sometimes also with the addition of water, since the softness of the herring under such conditions must be assumed to have an insignificant influence on the course of freezing.

The exact placements of the individual temperature points

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*Tr.: Forfangstsild: lean young herring, caught along the West Coast of Norway in late April/May, after normal spring herring season.

were measured upon the removal of the frozen herring after the test. In total, 58 test lots were frozen and a further 10 equalization experiments were carried out. Ten to twelve of the tests were unsuccessful due to various accidents with the measuring equipment, power failures, etc., and have not been included in the calculations.

The course of freezing.

For each section and experiment the read or recorded temperatures were drawn in on a time diagram. Examples are shown in Fig.3 - 6 (see last pages), for boxes and covered and uncovered cartons. Ordinarily, in each experiment measurements were carried out in 6 - 7 sections, of which 3 - 4 were in the mid-section under somewhat uniform conditions. Of course the herring freezes faster near the edges of the box than in the middle, due to 3-dimensional heat transferrence. But minor deviations were also usually found between sections which were somewhat equally placed in the mid-section. This was due to the fact that filling was necessarily somewhat uneven and the air current also was not completely uniform. The difference in freezing time for the two sections that froze last was, however, rarely above 5%.

Based on the time diagram and the placement of the thermocouples, isotherms were also drawn in on a time-thickness diagram (see figures 3 - 6). Such diagrams are quite suitable to extract the freezing time for the layer which freezes last, since one cannot always count on being so lucky as to have a

TABLE II

Overview of experiments in varying velocity air-blast freezing in tunnel of herring.

Exp. no.	Packaging	Weight of herring kg	Mean start. temp. t_1 °C	Air velo. m/sec.	Mean air temp. t_L -°C	Freezing time to max. temp in herring -4°C	-12°C	-20°C	Freezing time corrected to t_1=10°C and T_L=-30°C freezing to -4°C	-12°C	-20°C	Comments
5	Crt.w/o lid	25	0	4.3	33.4	5.8	7.3	7.7	7.2	9.0	9.5	Fresh, dry large herring
7	Box w/lid	52	5	4.3	33.0	24.8	28.1	31.2	28.9	32.7	36.3	Fresh,large herring, packed w/parchment paper.
9	Box w/o lid	52	5.4	12	32.5	10.6	11.5	-	12.1	13.1	-	Fresh, bait-free fat herring.
11	" "	52	0.7	5	33.0	14.1	15.5	-	17.1	18.8	-	4 day-old, bait-free fat herring.
13	" "	52	-0.2	7	31.3	12.4	13.2	-	14.3	15.3	-	Quite fresh,bait-free fat hr.,small
14	" "	52	0.4	2	31.8	20.7	23.5	-	24.2	27.5	-	2-day-old,small, bait-free fat hr.
15	Box.w/lid	52	2.2	7	32.3	22.1	23.2	-	25.8	27.1	-	Fresh, small fat hr., some bait.
16	Crt.w/o lid w/w	23	7.5	12	32.9	7.0	7.3	-	7.9	8.3	-	1 day,bait-free fat hr.,+ 8kg water.
17	Crt. w/o lid	23	2.9	12	31.9	4.5	5.1	-	5.15	5.9	-	2 days, bait-free fat hr.,small.
18	" "	23	9.9	12	33.9	4.9	5.3	-	5.6	6.1	-	Same hr. as 17, 2nd. freezing.
20	Crt. w/lid	23	2.1	5	32.0	13.5	14.3	-	15.6	16.6	-	1 day, bait-free,small, fat hr.
21	Crt. w/o lid	23	2.2	5	33.4	6.4	7.1	-	7.7	8.6	-	2 days,bait-free,small, fat hr.
22	Crt. w/lid	23	3.1	2	34.2	17.3	18.5	-	21.2	22.8	-	Quite fresh, fat hr., bait-free.
23	Crt w/o lid	23	2.5	2	31.0	11.3	12.3	-	12.6	13.7	-	Quite fresh,small bait-free fat hr.
24	Crt.w/o lid w/w	23	4.8	5	32.8	9.6	10.0	-	11.1	11.6	-	Quite fr. bait-free fat hr.+ 8kg. water
26	" "	23	1.3	2	33.7	12.9	13.5	-	15.9	16.7	-	" " " " " "
27	Crt. w/o lid	23	0.7	7	30.6	6.2	6.7	-	6.9	7.5	-	2 days,bait-free small fat hr.
28	Crt.w/o lid w/a	20	4.3	12	29.8	7.7	8.4	-	8.05	8.8	-	Fresh,bait-free small hr.,+ 7-8 kg alginate solution.
29	" " "	20	1.2	2	32.6	13.6	14.8	-	16.2	17.7	-	Fresh, bait-free small hr. + 7-8 kg alginate solution.
30	" " "	20	4.2	5	33.5	9.6	10.2	-	11.4	12.2	-	2 day,bait-free small hr.,+ 7-8kg alginate solution

hr. = herring
w/w = with water
w/a = with alginate

Table II (cont.)

Exp. no.	Packaging	Weight of herring kg	Mean start. temp. t_1 °C	Air velo. m/sec.	Mean air temp. t_L °C	Freezing time to max. temp in herring -4°C	-12°C	-20°C	Freezing time corrected to t_1=10°C and T_L=-30°C freezing to -4°C	-12°C	-20°C	Comments
32	Crt. w/lid	0	16	6	41.0	11.2	11.9	12.4	14.9	15.9	16.6	Carton filled with alginate sol.
33	Box w/lid	54	3	7.5	36.0	20.2	21.7	23.2	26.4	28.3	30.3	Fresh fat herring, 7 per kilo.
34	Crt.w/lid w/w	25	11.0	7.5	40.0	10.4	11.0	11.5	14.1	14.9	15.6	Same as 33, soft.Crt.filled w/water.
35	Crt.w/o lid w/w	25	9	7.5	39.8	7.2	7.5	7.8	9.9	10.4	10.8	Same as 33,very soft. "" ""
36	Box w/o lid	53	0.5	8	39.0	9.4	10.6	11.3	13.7	15.5	16.5	Fat herring 12-13 per kg, fresh.
37	Crt. w/lid	23	4	8	38.0	9.8	10.9	11.8	13.4	14.9	16.2	Same hr. as 36. A bit soft.
38	Crt. w/o lid	23	10	7.7	37.0	4.7	5.1	5.5	5.9	6.4	6.9	Same hr. as 36. Somewhat soft.
39	Crt.w/o lid w/w	23	10	5.5	39.0	7.7	8.0	8.3	10.2	10.7	11.1	Same hr. as 36,very soft,+ 6 kg w.
40	Crt. w/o lid	22.5	9	6	39.8	4.2	4.7	5.1	5.8	6.5	7.1	Same hr. as 36, very soft.
42	Box w/o lid	51	1	6.5	40.0	10.1	10.5	10.9	15.1	15.7	16.3	Fresh hr. 10 per kg.
43	Box w/lid	51	7	7	40.0	17.6	18.9	20.3	24.8	26.6	28.6	Same hr. as 42, a bit soft.
44	Crt w/lid w/w	24	8	6.5	40.0	12.6	13.0	-	17.6	18.2	-	Same as 42, soft, w/3.2 kg w.
45	Crt. w/lid	24.5	6	2.5	39.0	12.7	14.0	14.7	17.6	19.4	20.4	Fresh herring.
46	Crt.w/o lid w/w	24.5	5	2.5	40.0	9.0	9.5	10.0	12.9	13.6	14.4	Same as 45, w/ 4.5 kg water.
48	Crt. w/o lid	24.4	5	2.75	40.0	7.5	8.4	9.0	10.8	12.1	12.9	New small hr., 24 per kg.
49	Box w/o lid	54	1	2.75	40.0	14.5	15.6	16.3	21.6	23.2	24.4	New hr., 12-13 per kg.
50	Box w/lid	52.5	3	3	42.0	20.4	22.4	23.6	31.5	34.6	36.4	Same hr. as 49, thawed.
51	Box w/o lid	53.9	7	0	32.5	31.8	34.9	38.5	35.7	39.2	43.2	New hr.,5-6 per kg."Still refrig."
52	Box w/lid	49	15	0	31.0	40.0	45.6	50.5	39.7	45.3	50.1	Same hr. as 51. "Still refrig."
53	Crt. w/lid	26	7	0	32.5	23.4	30.2	34.5	26.3	33.9	38.8	Same hr. as 51. "Still refrig."
54	Crt. w/o lid	26	6.5	0	30.5	17.9	21.6	25.0	18.8	22.7	26.3	Same hr. as 51. "Still refrig."

hr. = herring
w/w = with water
w/a = with alginate

thermocouple placed just here, but when the isotherms are drawn in, a fairly true correction can be achieved when the thermocouples are not too far from the correct point. This is particularly important when freezing with a lid on, where the layer which freezes last will be lying heavily displaced towards the top of the box due to the far poorer heat transferance through the stationary layer of air on the upper side, (Figure 3 and 5). With a bit of experience it is also possible to observe from the shape of the freezing curve whether the point is sufficiently close to the middle layer.

It is, of course, impossible to obtain exactly the same mean starting temperature and air temperature in all experiments. In order to obtain a uniform basis for comparison, it is therefore necessary to correct the freezer time to the same conditions; a selected starting temperature $t_1 = 10^{\circ}C$ and the air temperature $t_L = -30^{\circ}C$. By using the following formula it can be made fairly accurate:

$$Z_{10,-30} = Z \cdot \frac{1 + A \cdot 10}{1 + A \cdot t_1} \cdot \frac{t_L - 3}{27}$$

which presumes a mean temperature of $-3^{\circ}C$ for the heat transfer, selected based on an estimated evaluation of the freezing curves. The mean temperature for heat transfer varied somewhat, of course, according to the final temperature selected for the freezing. This variation is, in this particular area, so small that it can safely be disregarded.

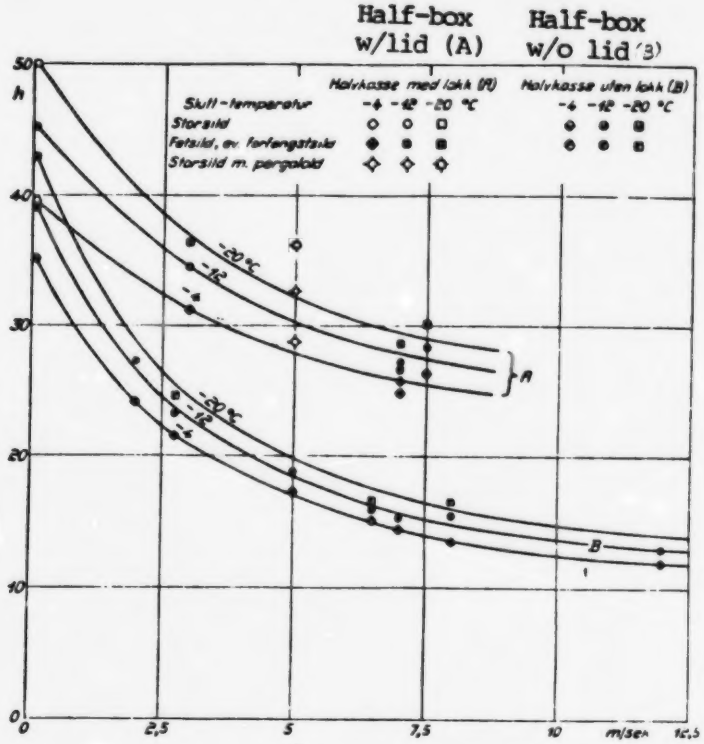
The coefficient A can, with the small deviation from 0°C which is involved here (t_1 = 0 to 16°C), be set at A = 0.01. Any error in this correction will also be of totally secondary significance and a more exact method of procedure therefore has no purpose.

An overview of conditions during the experiments and the measured and calculated freezing times at the various maximum final temperatures are shown in Table II.

The influence of air velocity on freezing time.

Fig. 7 shows how the freezing time is dependent on air velocity when dealing with half-boxes with and without lids. Figure 8 shows corresponding results for cardboard boxes. Both diagrams apply to temperatures t_1 = 10°C and t_L = -30°C.

In both diagrams there is a noticeable difference in the sharpness of the curves for freezing with and without lid. The latter, in particular, drops significantly faster at rising air velocity than expected for homogeneous material of corresponding thickness. The reason for this is obviously air currents between the individual herrings, which, particularly at high air velocity, play a significant role in the freezing process of products in open packaging. In half-boxes with lids, which have some slotted openings in the tops and bottoms, the forced air current still has a certain significance, while for the closed cartons the air current is mainly due to self-convection in the herring mass and must be assumed to be quite insignificant.



Final temperature
Large herring
Fat, or young, herring
Lrg. herring w/ pergaloid

Fig. 7. The curves indicate how the freezing time from 10°C to a determined core temperature (-4, -12 and -20°C) depends on the air velocity, for standard half-boxes with lids (A) and without lids (B). The air temperature is -30°C. The points of experiment are drawn in. As is evident the type and size of the herring is of secondary significance. In the case of "still" refrigeration the difference in freezing time for boxes with and without lids is rather small. At higher air velocities, however, the herring freezes almost twice as fast when the lid is not on.

The same difference is clearly evident when comparing freezing in open cartons with and without the addition of water or alginate jelly. When the empty spaces are filled, convection ceases completely and a velocity dependency is obtained corresponding to that for a block of homogeneous material.

As can be expected, the reduction in freezing time at higher air velocity is relatively greatest for thin packages where heat-conduction-resistance in the product to be frozen has a relatively low impact. At high velocities, air swirls in over the herring mass have a similar effect; it is obviously most

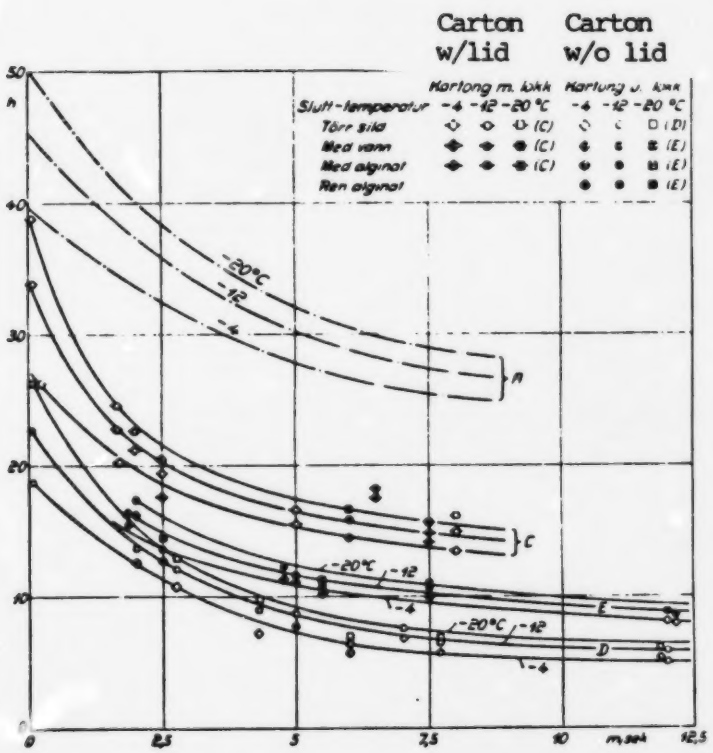


Figure 8. Freezing time for herring in cartons, under the same conditions as specified in Fig. 7. The curves C apply to cartons with lids, regardless of water or alginate solution added, or whether the herring was dry. Curves D apply to dry herring in cartons without lids. If freezing without lid, but with water or alginate added, then curves E show the freezing time. The freezing time for half-boxes with lids is shown as comparison by the broken lines, taken from diagram 7 (A).
A noticeable reduction in freezing time at high air velocities when freezing without lid, particularly in dry herring, is evident.

effective when the layers are not too thick. It is therefore more rational to build a freezer of considerably higher velocity for open cartons than that for boxes or closed packages.

At high velocities, block-freezing using alginate or 14.
water results in a longer freezing time than for dry herring in open packaging. The freezing time for closed cartons with and without alginate or water added are practically the same. On the other hand, the requirement for cold is, of course, greater and the capacity in tonnes of herring for a given plant is less when liquid is added. In the conditions studied, the requirement for cold increased by 20 to 50%.

15.

The influence of temperature.

The influence of the starting temperature and the air temperature is relatively easy to calculate with sufficient accuracy within the areas studied. The effect of the final temperature is not so great when the temperature in the core is below $-4^{\circ}C$, as shown in diagrams 7 and 8.

Figures 9 to 13 show how the freezing time is dependent on air temperature and velocity for the forms of packaging studied, when freezing down to $-12^{\circ}C$ in the core; a reasonable maximum final temperature for products to be placed in storage. A satisfactorily low mean temperature will then be obtained. 17.
Starting temperature is assumed to be $t_1 = 10^{\circ}C$; rarely exceeded in practice.

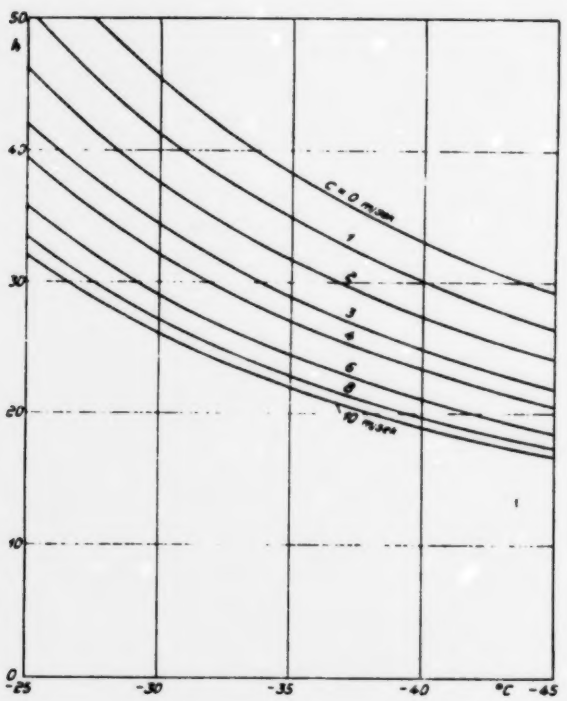


Fig.9. Necessary freezing time for herring in standard half-boxes with nailed on lids, depending on air temperature and velocity. A starting temperature of 10°C and a final temperature in the core of -12°C is assumed. A reasonable mean temperature for storage after the conditions have equalized is thereby obtained.

The way freezing is often carried out in practice, at -25 to -30°C air temperature and a relatively low velocity, freezing time of about 48 hours must be expected. Only by using particularly low temperature (about -40°C) and air velocity greater than about 4m/sec can the freezer time be reduced to about 24 hours, using this type of packaging.

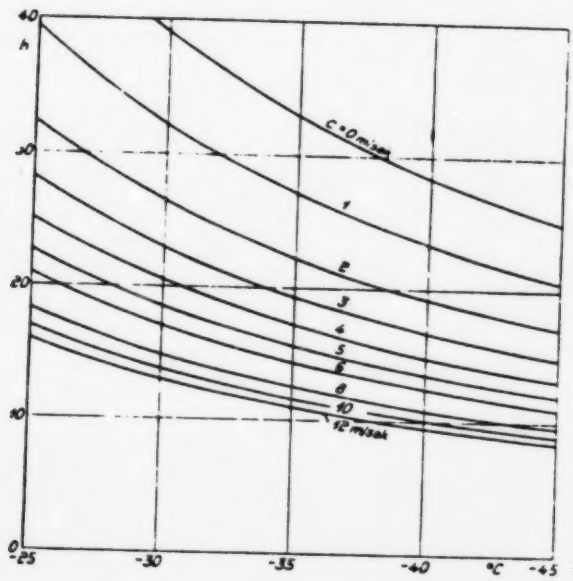


Fig. 10. Necessary freezing time for standard half-boxes without lids under the same conditions as specified in fig. 9. In common practice (-25 to - 30°C and relatively low air velocity) a freezing time of about 24 hours, must often be expected; up to 48 hours for "still refrigeration". At particularly low temperature (-40°C) and very high air velocity (above ca. 7m/sec.) the freezing time can be reduced to about 12 hours.

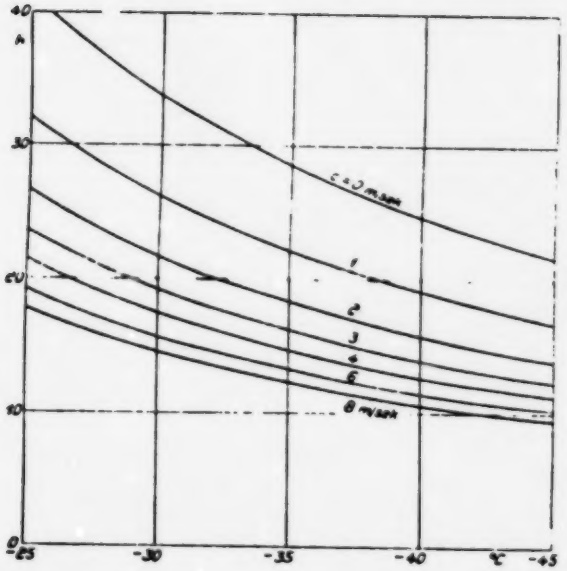


Fig. 11. Necessary freezing time for herring in 105mm high cardboard cartons with lids, with and without alginate or water at various temperatures and air velocity. Conditions otherwise ..... (Remainder illegible. Tr.)

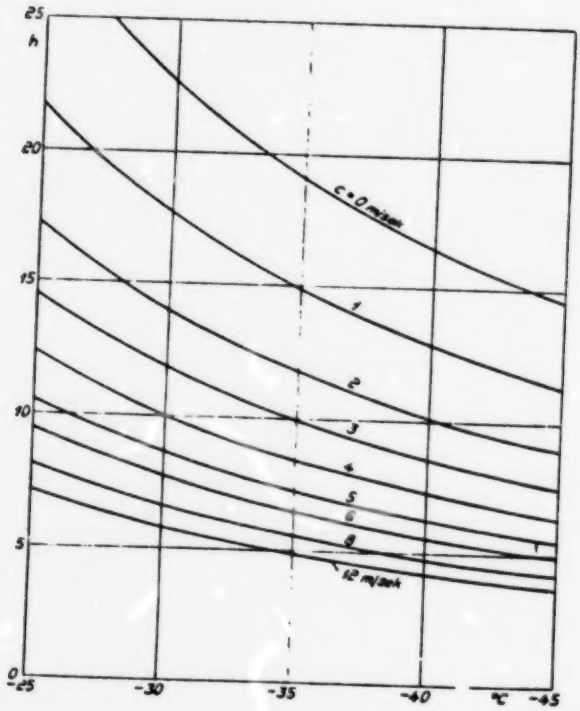


Fig.12. Necessary freezing time for dry herring in open cartons 105 mm high, as a function of air temperature and velocity. Conditions otherwise as specified in Fig. 9. When using particularly low temperature (-40°C) and air velocity above approx. 6 m/sec. freezing time can be reduced to about 6 hours.

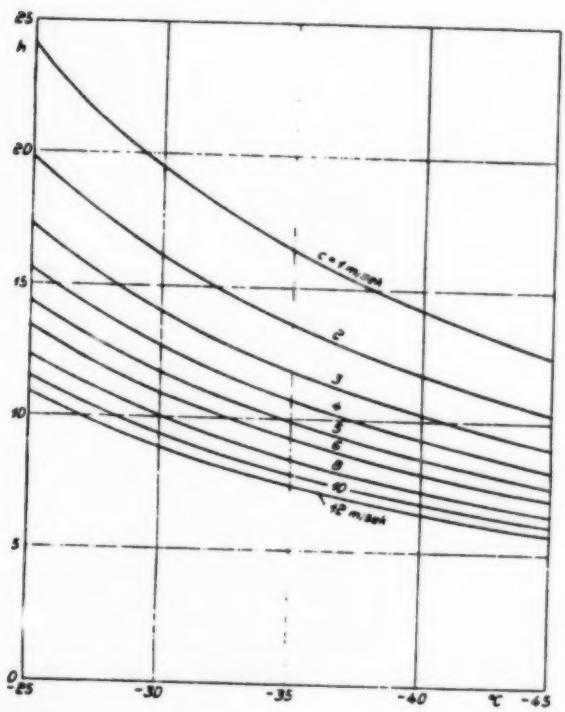


Fig.13. Necessary freezing time for herring in water or alginate and open cartons, as a function of air temperature and velocity. Conditions otherwise as specified in Fig. 9. Freezing time significantly longer than for dry herring at greater velocities.

As is evident, the freezing time for half-boxes with nailed on lids cannot be reduced below 24 hours, even with a temperature of -40°C and extremely high air velocities. The way freezing is carried out at present, with low air velocity and a temperature of between -25 and -30°C, freezing must be expected to take 48 hours (fig.9).

For standard half-boxes with no lids, the freezing time can be reduced to about 12 hours at high air velocity and -40 to -45°C. Under normal conditions and at most plants, freezing times must be expected to be considerably more than 24 hours (fig.10).

For 105 mm high open cartons the freezing time can, under favourable conditions, be reduced to about 6 hours (fig.12).

Freezing by air-blasting. 18.

As shown, and in consideration of the proven strong effect of convection between the individual herrings in open packaging, the logical next step was to try freezing by direct air circulation through the boxes. A series of tests was carried out using the arrangement shown in Fig. 14. The herrings were packed in half-boxes, some with a bottom of fine wire mesh, others with normal slotted bottoms using 5 slats, each 10 mm wide. The box was placed in a frame and sealed around the edges by packing tightly with packaging material. The cold air was forced upwards through the herring mass from below. The amount of air was determined by a diaphragm built into the channel and the loss of pressure above the box by micro-manometer.

The temperature in the herrings was recorded at 30 points, randomly distributed throughout the whole box. The thermocouples were placed in the middle of the individual herring when possible. In addition, the air temperature before entering and after exiting the box was recorded. The course of temperature at the individual points during one of the experiments is shown in fig. 15. 19.

Some results of the measurements are compiled in Table III. Conversion to mean air temperature of $-30^{o}C$ was made in the same manner as before. As is shown, freezing time to $-12^{o}C$ maximum temperature is reduced all the way to 4.2 and 6.4 hours for the best and the poorest of the boxes, respectively, which is a fraction of the time needed for air freezing by the normal method.

The table also shows the calculated nominal air velocity for a free box cross-section. The figure includes some seepage past the box, which is almost impossible to avoid. The temperature difference in the air immediately before entering and after exiting the box was therefore also somewhat greater than in the total amount of air measured. The seepage was greatest during the first experiments, and was gradually reduced as the experiments went on. The amount of air which actually passed through a herring mass corresponds to a nominal velocity not likely to exceed 0.5 m/sec.

True air velocity between the herrings is, of course, significantly greater than the nominal velocity calculated. Immediately above the box a vertical velocity was measured which varied randomly in spurts over the cross-section between 0 and

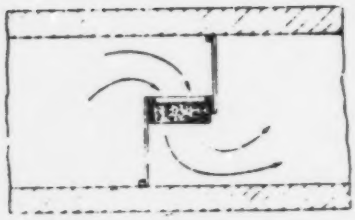


Fig.14. Schematic set-up for experiment of freezing herring in half-box (ordinary "freezer-box") by air-blasting.

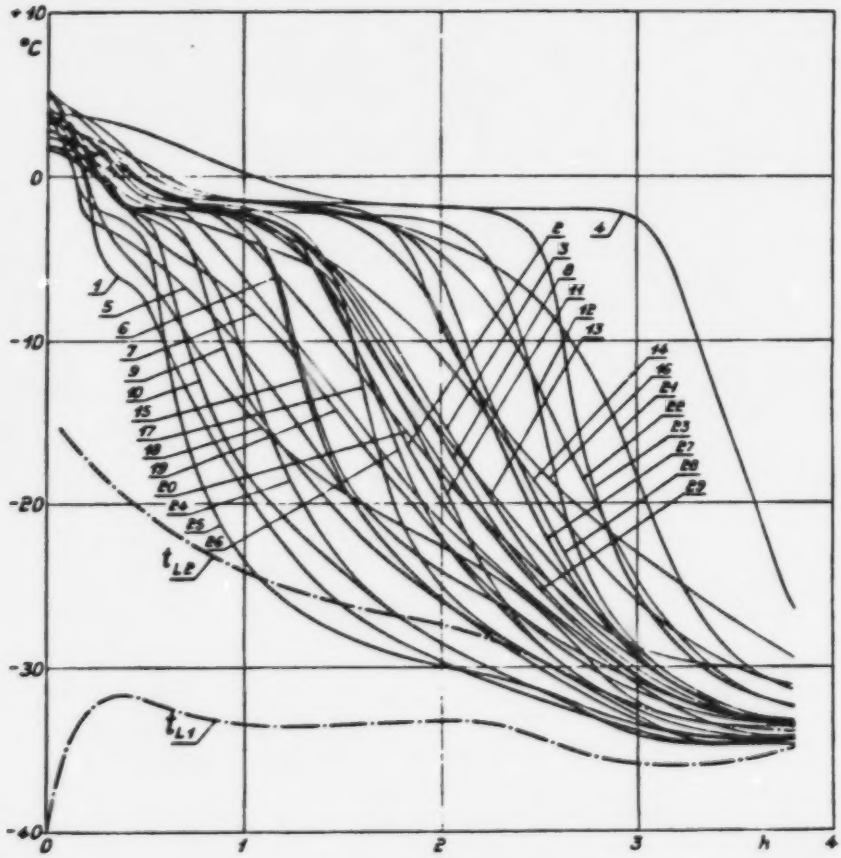


Fig.15. Course of temperature for 29 points in the box when freezing winter herring by air-blasting. Temperature measured in the middle of the imndividual herring. Measuring points distributed throughout entire box. t_{L1} and t_{L2} are air temperatures measured before entering and after exiting the box. As seen, freezing time for the individual points are very varied, depending on air current conditions around each individual herring. Necessary time for complete freezing through is however significantly shorter than by conventional freezing method and the same packaging.

about 6 m/sec, corresponding to the distribution of channels in the herring mass. The air current exited in the form of randomly distributed thin rays in various directions. The course of the freezing process for the individual measurement points showed a corresponding variation, as shown in Fig. 15.

Experiments no. 55 and 56 were carried out using large herring (3.4 per kilo), no. 57 and 58 used spring herring (5.7 per kilo). The freezing times in the latter experiments were significantly longer than in the first, about 6 hours as opposed to 4 3/4 hours, due to the greater tendency of the softer herring to collapse and stick together. Therefore sections less penetrable to the air occur and individual spots will lag behind in the freezing process. This is exactly the same as occurrs during normal brine-freezing.

It is likely that a further significant reduction in freezing time could be obtained by pre-cooling the herrings 20.
before they are packed in boxes, particularly when dealing with a somewhat soft and small product. The strong tendency to stick together can then be avoided and less resistance and more even air distribution are obtained.

This new method should be easy to utilize in practice when constructing appropriate freezers, and is not likely to cause any great difficulties. It could contribute to solving the problem of a more efficient and qualitatively satisfactory system for "bulk freezing" of fish types such as herring, mackerel, small pollack and the like.

TABLE III

Experiments with air-blast freezing.

Exp. no.	Packaging	Weight of herring kg	Mean start. temp. t_1 °C	Nominal air vel. m/sec.	Press. loss through-out box mm H_2O	Mean air temp. t_L °C	Freezing time in hours to highest temp. in herring = -4°C-12°C-20°C			Corrected freezing time to t_1=10°C and and T_L=-30°C when freezing to -4°C-12°C-20°C			Comments
55	Box with wire mesh bottom no lid	51.7	3.0	1.0	33.2	36.5	3.21	3.90	4.40	4.26	5.18	5.84	Large herring, 3.4 per kg.
56	Normal freezer box no lid	51	3.5	0.8	37.4	34.0	3.15	3.40	3.60	3.84	4.15	4.30	Large herring, 3.4 per kg.
57	Normal freezer box with no lid	52	6.0	0.8	37.2	29.0	5.15	6.40	6.88	5.15	6.40	6.88	Spring herring, 5.7 per kg.
58	Normal freezer box with no lid	52	7.5	0.5	40.3	33.0	4.08	5.16	5.84	4.63	5.87	6.64	Spring herring, 5.7 per kg.

Temperature equalization after freezing.

Upon removal from the freezer, the temperature in the product will normally be fairly uneven, the surface will be strongly cooled down while the temperature in the core will be significantly higher. For a product as uneven as herring it is often only a single or a few spots which lag behind. To examine how long it will take for the condition to become somewhat equalized after the product has been placed in storage (provided it is stacked so that it does not obtain any significant cooling from the outside), several measurements were taken. The box was placed in a container which was heavily insulated on the inside with a light material of low heating capacity (rock wool), and which had been cooled down ahead of time to about the mean temperature expected after equalization. The container holding the box was also placed in the freezer during the equalization time to avoid any form of heat penetration from the outside. An example of the course of the temperature curves is shown in Fig. 16 (see last page).

Equalization within a section takes place relatively quickly, and is fairly complete within 3-4 hours. Between individual sections it takes a considerably longer time, due to the longer conductivity route and it may take up to 48 hours before the temperature is completely even throughout the whole box.

The temperature balance which takes place after a while, depends, of course, on the distribution of the temperature, and

the highest temperatures in the core play a relatively large role when not very much below the freezing point. Any unfrozen spots would be very unfortunate due to the large amount of cold that they demand, even if they are relatively small. It is therefore very important that the product not be removed from the freezer too early. It should be mandatory that the temperature after equalization be no higher than the presumed storage temperature, since cooling down when in stacks in a storage room will be very slow.

TABLE IV.

Overview of temperature equalization experiments.

Exp. No.	Packaging	Freezer temp. -°C	Measured herring temp. after freezing. -°C		Equaliz. temp. -°C	Comments
			Highest	Lowest		
U 1	Box	31.7	7.5	29.5	22.0	Dry herring
U 2	Box	32.5	5.6	27.2	20.5	Dry herring
U 3	Carton	32.7	12.8	28.5	25.5	Dry herring
U 4	Carton	34.2	7.5	28.0	21.0	Dry herring
U 5	Carton	40.0	11.0	31.0	21.0	Dry herring
U 6	Carton	40.0	15.0	32.5	27.0	Herring + water
U 7	Carton	40.0	16.0	36.0	29.0	Herring + water
U 8	Carton	35.5	2.0	23.0	13.0	Dry herring
U 9	Carton	40.0	8.0	31.0	25.0	Dry herring
U 10	Box	42.0	11.0	35.0	25.0	Dry herring

The result of 10 equalization experiments are shown in 23
Table IV, and fig.17. shows approximate correlation between highest core temperature and the equalization temperature. It appears that about the same mean curve can be expected for boxes and cartons when freezing in air at -30 to -40°C. The dispersion is no greater than expected for such experiments.

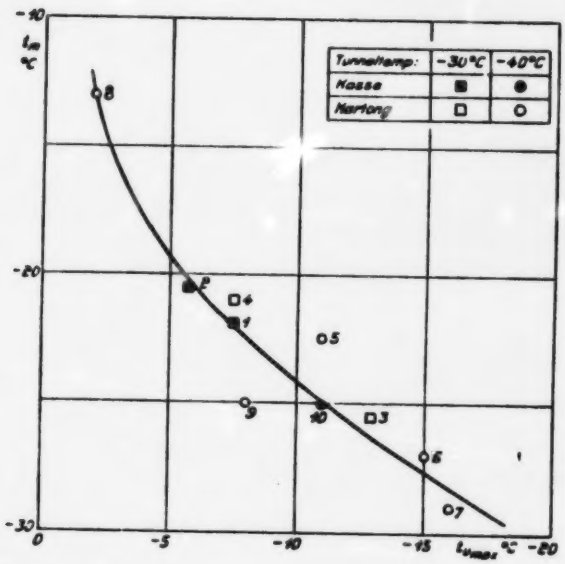


Fig. 17. Correlation between the equalization temperature and highest core temperature at time of removal from freezer, for herring in half-boxes and cartons. Freezing is carried out at tunnel temperature of about -30°C and about -40°C, respectively. It appears that the results for both types of packaging and temperatures can be given sufficiently accurately for practical use by a single curve.

As can be seen, a core temperature lower than -10 to -15°C should be demanded to obtain satisfactory results. The practice, which has been maintained, of calculating the freezing time to -4° C core temperature, is therefore very dangerous, and may lead to considerable quality loss.

24.

Conclusion.

The tests showed that when changing to more appropriate, thinner, packages a significant reduction in freezer time can be achieved by conventional air-blast freezing. By converting from standard half-boxes with an inside height of 165mm to a compressed cardboard box with a height of 105 mm, the freezing time could be reduced by 50 to 70 %. The reduction was greatest at high air velocity.

It was found that by freezing packages with no lids the convection down into the herring mass provides a significant contribution to heat transfer, which significantly reduces freezing time. For that reason it is advantageous to use significantly higher air velocity than that which was previously assumed. During block freezing using water or alginate jelly a reduction in the freezer capacity must be expected and a high air velocity provides less advantages than for dry herring.

By direct air-blasting it is possible to obtain a significant reduction in freezing time, even in packaging with relatively high sides. Freezing periods of less than 4 hours were

measured for large herring in standard half-boxes. The new method ought to find use in practical and qualitatively satisfactory "bulk freezing" of herring, mackerel, etc..

By virtue of the advantages inherent in freezing in open packaging, air-blast freezers for herring should be built with particular consideration to control of the frosting problem.

The temperature in the herring is almost completely equalized within the first 48 hours after removal from the freezer. It is necessary to arrive at a satisfactorily low storage temperature and to carry out freezing down to a temperature which does not exceed -10 to -15^{o}C in the core.

Summary in English.

Summary in English.

The purpose of this work is to provide more accurate data for the calculation and design of air blast freezers for herring and similar fish. 58 samples were frozen in the following types of packing:

50 kg standard, wooden herring boxes without lid.
50 « « « « « with lid on.
22 kg flat cardboard boxes without lid.
22 « « « « with lid on.

For the two latter types, tests were made also to ascertain the influence of adding water and alginate jelly to the herrings for «block freezing». The dimensions of the boxes are given in *Table I*.

Two different blast tunnels were used in the tests, as shown in *Figs. 1 and 2*. Air temperature was varied from —30 to —42°C, velocity from 0 to 12 m/sec. Different types of herrings were used, according to season and availability. A survey of test conditions and main results is given in *Table II*.

The temperatures in individual herrings and air were recorded by means of thermocouples, to an accuracy of $\pm$ 1/2°C. The thermocouples were distributed over 6 or 7 cross-sections of the box. Examples of the temperature development during freezing are given in *Figs. 3 to 6*, for each of the types of package mentioned.

Figs. 7 and 8 give the necessary freezing time as a function of air velocity for an initial fish temperature of 10°C and mean air temperature —30 C. The curves correspond to a maximum recorded final temperature of —4, —12 and —20°C, respectively. Each set of curves correspond to the following conditions:

A: Standard boxes with lid.
B: Standard boxes, open.
C: Cardboard boxes with lid, with or without water or alginate jelly added.
D: Open cardboard boxes, dry herring.
E: Open cardboard boxes, herring + water or alginate jelly.

Safe freezing time as a function of air temperature and velocity for the

same conditions and a maximum, final core temperature of —12 C is recorded in *Figs. 9 to 13.*

The results show that the influence of air velocity on the freezing rate in open containers is considerably greater than for a solid, homogenious slab, obviously as a result of convection between the herrings. In an effort to further increase this effect, freezing by air blast through the herring mass was tried. The arrangement is shown in *Fig. 14*, the results of 4 tests are given in *Table III. Fig. 15* is a diagram of herring and air temperatures for one of the boxes.

It was found that the freezing time can be reduced very considerably by this new method, to as low as 4,2 to 6,4 hours for —30°C air, depending on the herring characteristics.

When the box is taken out of the freezer, the temperature in the fish is rather uneven. It is of practical interest to know to what maximum core temperature the fish must be cooled, to arrive at a sufficiently low storage temperature after equalisation. Additional heat removal in storage, when the boxes are tightly stacked, will necessarily be extremely slow, and should be avoided.

An example of temperature relaxation after freezing is given in *Fig. 16.* While the equalization over the individual cross-section is fairly complete after 3 or 4 hours, the time for total equalization within the whole box is considerably longer.

Results of 10 relaxation tests are given in *Table IV and Fig. 17.*

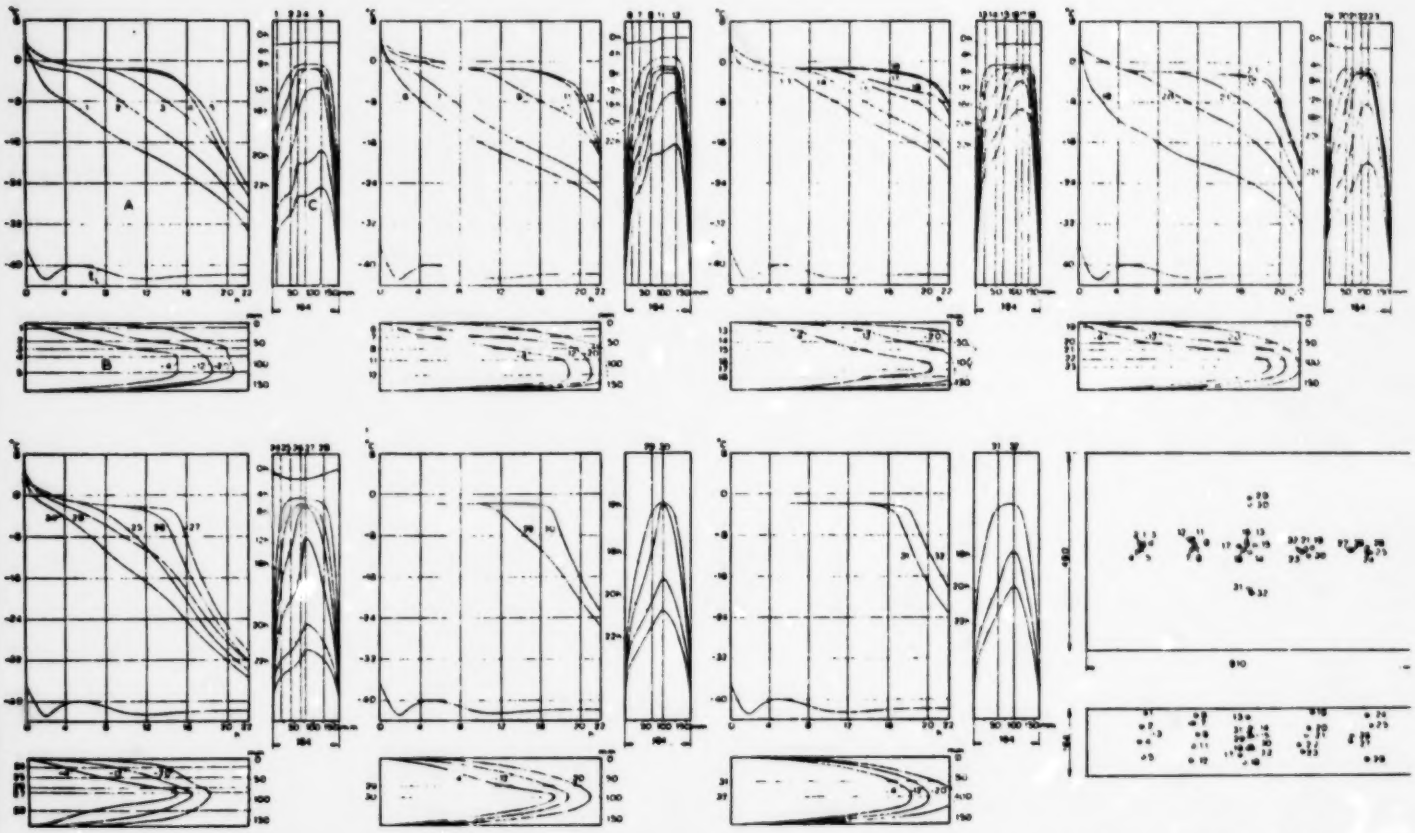


Fig.3. Typical curves for freezing 52.5 kg herring in standard half-boxes with lids on (experiment no. 50). The thermocouples were placed in the herring as shown in the sketch at lower right, distributed over 7 cross-sections. For each section a temperature course as a function of the time for the individual measurement points (Diagram A), isotherms in time-thickness diagram (B) and isochrones in temperature-thickness-diagram (C) are drawn in. Mean air temperature during the test was t_L=-42.0°C, air velocity 3m/sec, freezer time at -12°C in the last freezing core section 22.4 hrs. The freezing time can be read most accurately from the isotherms. The freezing was asymmetric due to the insulating layer of air under the cover. In addition some random variations exist between the individual cross-sections, reflecting the normal unevenness in packages loosely filled with herring.

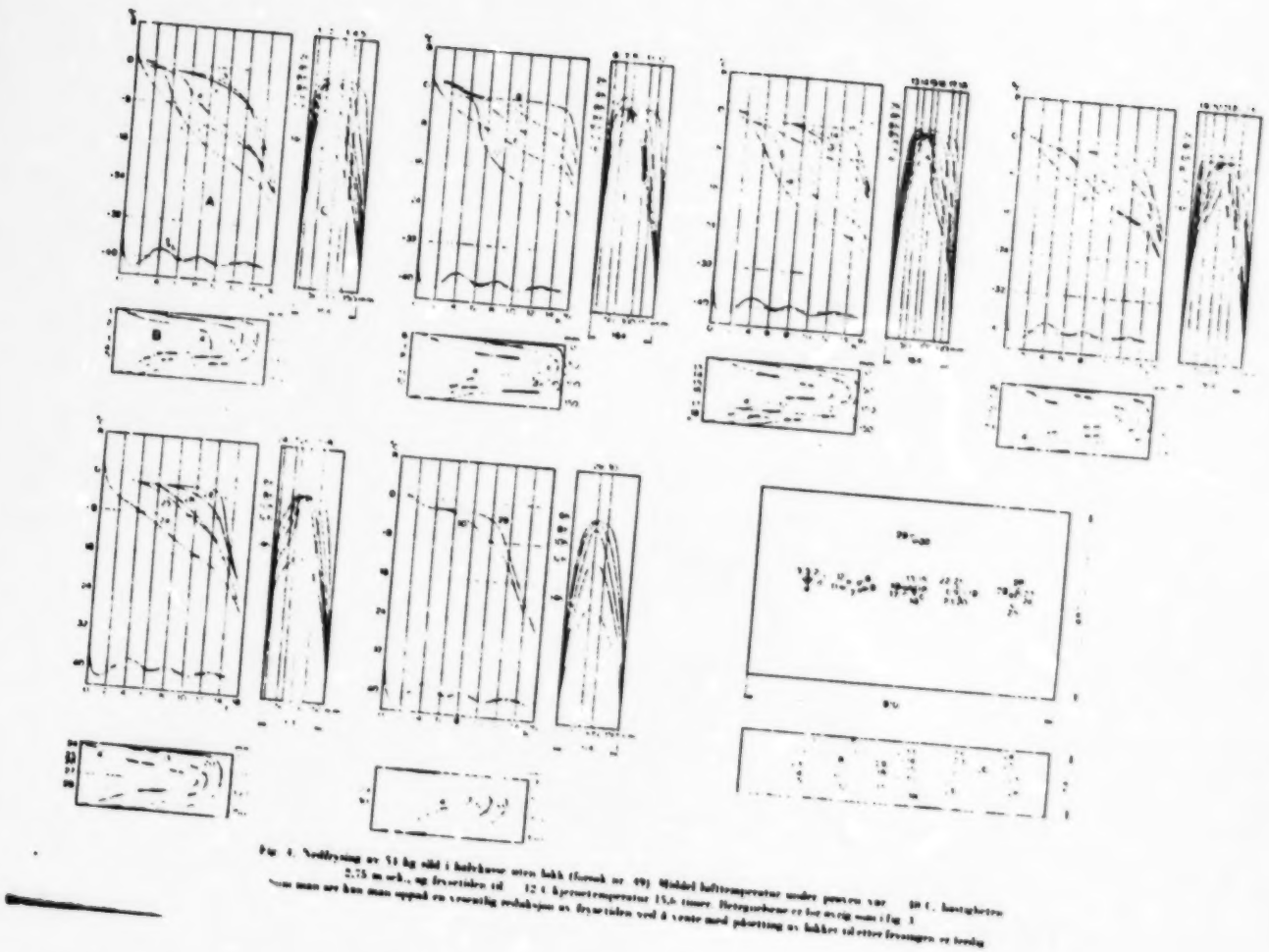


Fig.4. Freezing of 54 kg herring in half-boxes without lids (experiment no. 49). Mean Temperature during the test was -40°C, velocity 2.75 m/sec and freezing time at -12°C core temperature was 15.6 hours. Notations are otherwise as for Fig.3. As is evident, a significant reduction in freezing time can be obtained when delaying putting on the lid until after freezing is completed.

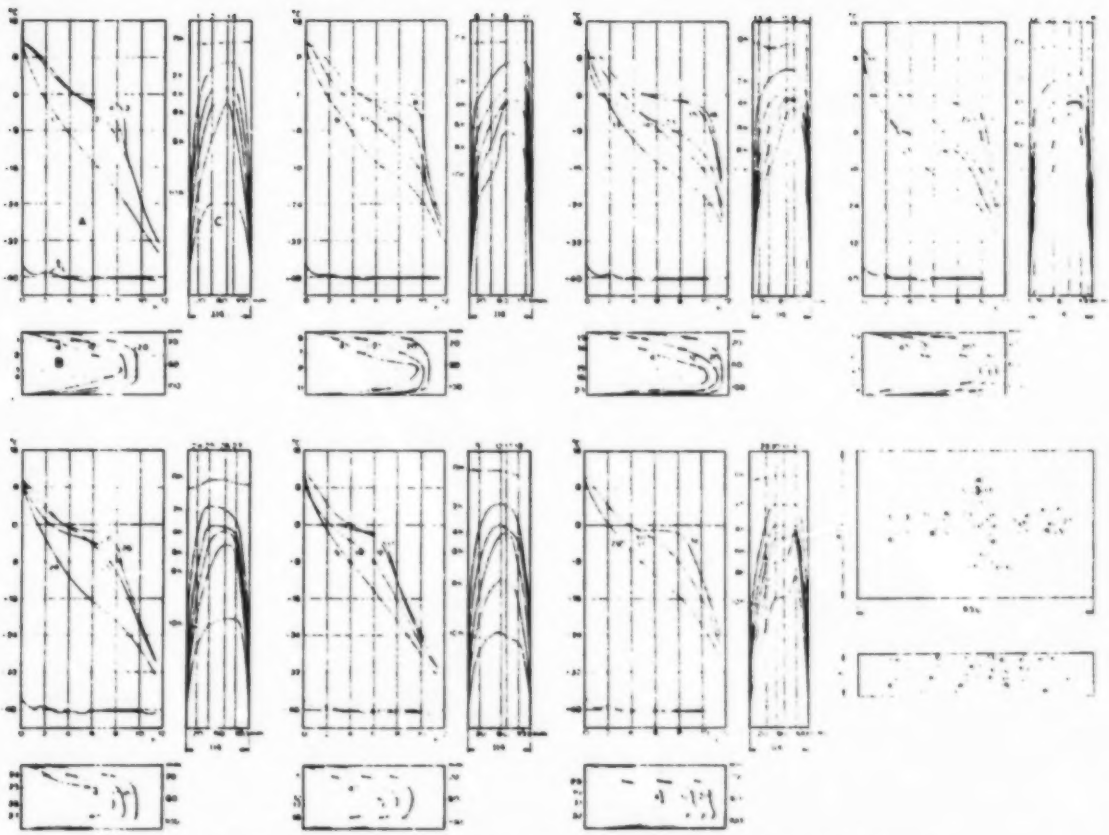


Fig.5. Freezing of 25 kg fat herring in cartons with lid on (experiment no.34). The empty spaces between the herrings were filled with fresh water. Mean air temperature during the test was -40°C, velocity 7.5 m/sec.and freezer time at -12°C in the core was 11.0 hours. Otherwise as in fig.3. Here, too, very asymmetrical freezing took place due to the insulating layer of air under the lid.

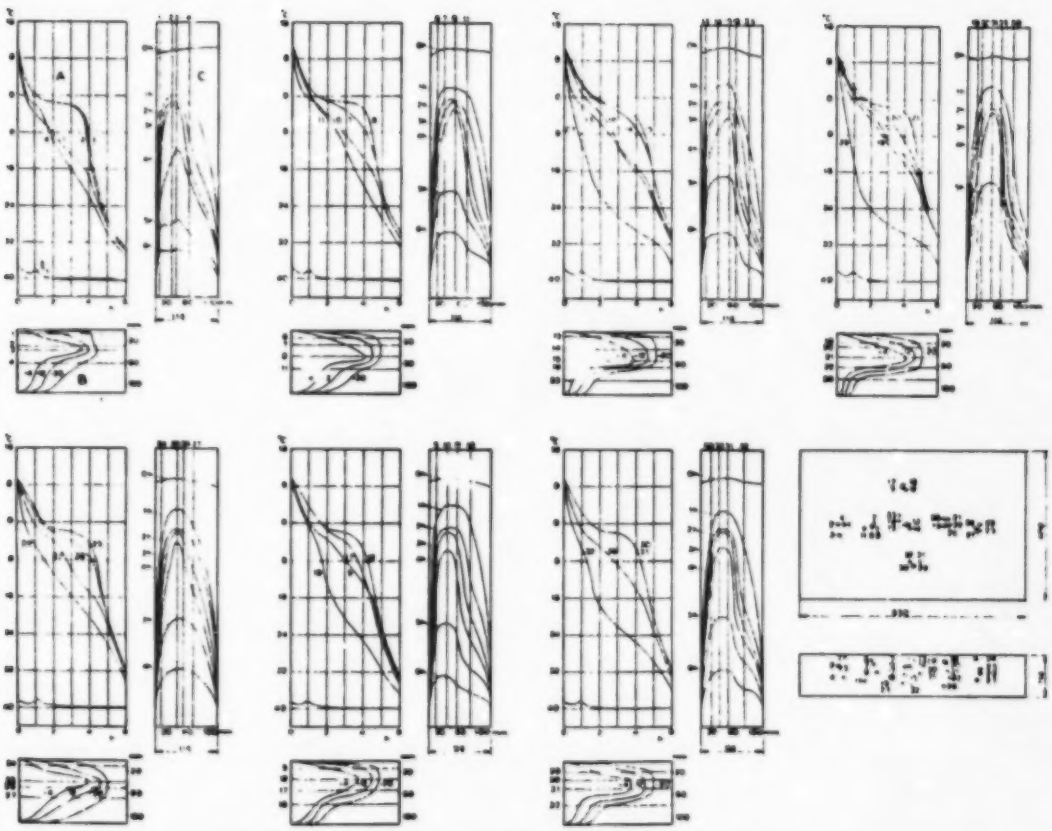


Fig. 6. Nedfrysing av 22,5 kg fersild i åpen kartong (forsøk nr. 40). Middel lufttemperatur under prøven -39,8°C, hastighet 6 m/sek. og frysetid til 12 t 4,7 timer. Øvrige forhold som i fig. 3.

Fig. 6. Freezing of 22.5 kg fat herring in open carton (experiment no.40). Mean temperature during the test was -39.8°C, velocity 6 m/sec. and freezing time at -12°C in the core was 4.7 hours. Otherwise as in fig.3.

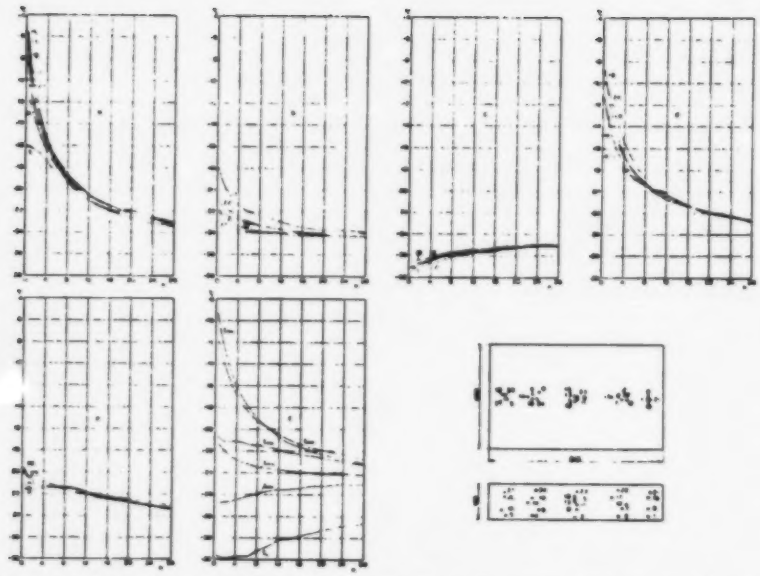


Fig. 16. Temperaturforløpet i en standard halvkasse etter avsluttet nedfrysing. Diagrammene a til e viser temperaturforløpet for 5 forskjellige tverrsnitt i kassen. Målepunktenes beliggenhet fremgår av figuren i nederst høyre hjørne. Diagram f viser hvordan middeltemperaturen for de enkelte snitt varierer og lufttemperaturen i lagerrommet t_L.
Mens utjevningen innen de enkelte snitt er nokså fullstendig etter noen få timer, krever utjevningen over kassens lengde og bredde vesentlig lengre tid.

Fig.16. Course of temperature in a standard half-box after completed freezing. Diagrams a to e show the course of temperature for 5 difference cross-sections in the box. The locations of the measurement points are shown in the figure in lower right corner. Diagram f shows how the mean temperature for the individual sections varied; air temperature in storage room was t_L.
While the equalization within the individual sections is fairly complete after a few hours, the equalization throughout the whole length and width of the box requires considerably longer time.